

ESTIMATING DUST ENRICHMENT AND WATER ICE ABUNDANCE IN THE PROTOPLANETARY DISK FROM OXYGEN ISOTOPE RATIOS AND FEO-CONTENT OF TYPE I CHONDRULES FROM TWO CV CHONDRITES. A. T. Hertwig¹, N. T. Kita¹, C. Defouilloy¹, and M. Kimura², ¹WiscSIMS, University of Wisconsin-Madison, Madison, WI 53706. (hertwig@wisc.edu), ²Ibaraki University, Mito 310-8512, Japan.

Introduction: CV chondrites contain coarse Ca,Al-rich refractory inclusion (CAIs) and up to mm-sized FeO-poor (type I) and FeO-rich (type II) chondrules [e.g., 1, 2]; however, type I chondrules are by far the most abundant [>95% in CV, 3]. Indicative for type I chondrules are high Mg#’s of >90 with the Mg# of a chondrule defined as the average MgO/(MgO+FeO) [mol%] of the ferromagnesian minerals. To facilitate crystallization of olivine with significant FeO contents, redox conditions during chondrule-formation had to be more oxidizing than those estimated for the protoplanetary disk with Solar elemental abundances [e.g., 4, 5]. The more oxidizing conditions recorded in the Mg#’s could be due to higher amounts of CI dust in the chondrule-forming region relative to Solar abundances (i.e., dust enrichment) [4, 6]. In addition, water ice, e.g., in the form of icy mantles surrounding precursor silicate grains, may have acted as an oxidizing agent (ice enhancement) [7, 8].

Recent high-precision oxygen isotope studies of chondrules in carbonaceous chondrites demonstrated that most chondrules possess olivine and pyroxene with homogeneous $\Delta^{17}\text{O}$ values ($=\delta^{17}\text{O}-0.52\times\delta^{18}\text{O}$; $\delta^{17,18}\text{O}=(R_{\text{sample}}/R_{\text{SMOW}}-1)\times 1000$, where $R=^{17,18}\text{O}/^{16}\text{O}$ and SMOW=Standard Mean Ocean Water), indicating that both minerals formed from an isotopically homogeneous melt [8–12]; hence, derived Mg#’s and oxygen isotope ratios probably reflect conditions during chondrule formation [8, 10]. Further, although being internally homogeneous, type I chondrules within a single chondrite usually show a range of different $\Delta^{17}\text{O}$ values. For type I chondrules in CR chondrites, [8] showed that the $\Delta^{17}\text{O}$ values continuously increase with decreasing Mg#’s (Fig. 1a). Applying results of equilibrium condensation calculations of [4], [8] developed a model involving an isotopic mass balance to predict dust enrichment and ice enhancement factors based on chondrule $\Delta^{17}\text{O}$ values and Mg#’s. At elevated dust enrichments (>100×), the essential oxygen isotope reservoirs in that mass balance are the ^{16}O -rich chondrule precursor dust (−5.9‰) and the ^{16}O -poor water ice (+5.1‰).

We analyzed the oxygen isotope ratios and Mg#’s of chondrules in two CV chondrites, Kaba (CV_{oxB}) and NWA 8613 (CV_{red}), to estimate possible dust enrichment and ice enhancement factors, utilizing the model of [8]. The possibility will be evaluated whether the var-

ying oxygen isotope ratios of chondrules in an individual chondrite could be caused by varying amounts of water ice associated with silicate precursors grains.

Methods: High-precision oxygen three-isotope analyses were conducted using a secondary ion mass spectrometer (WiscSIMS) following procedures described in [11, 13]. The spot size of 10–15µm allowed for multiple measurements within single chondrules and the calculation of representative chondrule $\Delta^{17}\text{O}$ values. Mg#’s of olivine and pyroxene were analyzed by electron microprobe.

Results: In Kaba 24 type I chondrules, 1 type II chondrule and 1 type II olivine fragment were analyzed; in NWA 8613 30 type I chondrules and 1 type II olivine fragment. In the examined NWA 8613 thin section, no type II chondrules are present (excluding the olivine fragment). In the following we will solely focus on type I chondrules.

In Kaba olivine and pyroxene have equally high Mg#’s of >98, indicating a low degree of thermal metamorphism experienced by this chondrite. NWA 8613 contains pyroxenes with usually high Mg#’s (>98) but Mg-Fe diffusion altered olivine Mg#’s to slightly lower values in between 88–99. Most of the chondrules in Kaba and NWA 8613 show internally homogeneous $\Delta^{17}\text{O}$ values, but minor occurrences of relict olivine grains that show $\Delta^{17}\text{O}$ values different from the chondrule means are identified. Excluding those isotopic relicts, most mean $\Delta^{17}\text{O}$ values of type I chondrules for both chondrites are in the range of −7‰ to −4‰; Kaba contains 2 chondrules with ^{16}O -rich compositions of about −8‰ and no type I chondrules with $\Delta^{17}\text{O}$ values higher than −3‰.

According to the model of [8] ($\Delta^{17}\text{O}$ value of silicate dust adjusted to −7‰), chondrule Mg#’s and $\Delta^{17}\text{O}$ values of both CV chondrites suggest 50–200× CI dust enrichment relative to Solar abundances and relatively dry condition (anhydrous to 0.4× water ice relative to CI dust) (Fig. 1b).

Chondrule formation in a moderately high dust-enriched disk: Like in most carbonaceous chondrites, the bulk of chondrules in Kaba and NWA 8613 are FeO-poor. While Mg#’s of the rare type II chondrules suggest high dust enrichments of >1000×, FeO-contents of type I chondrules indicate one order of magnitude lower dust enrichments compatible with chondrule formation models that involve shock-wave heating of the disk [14].

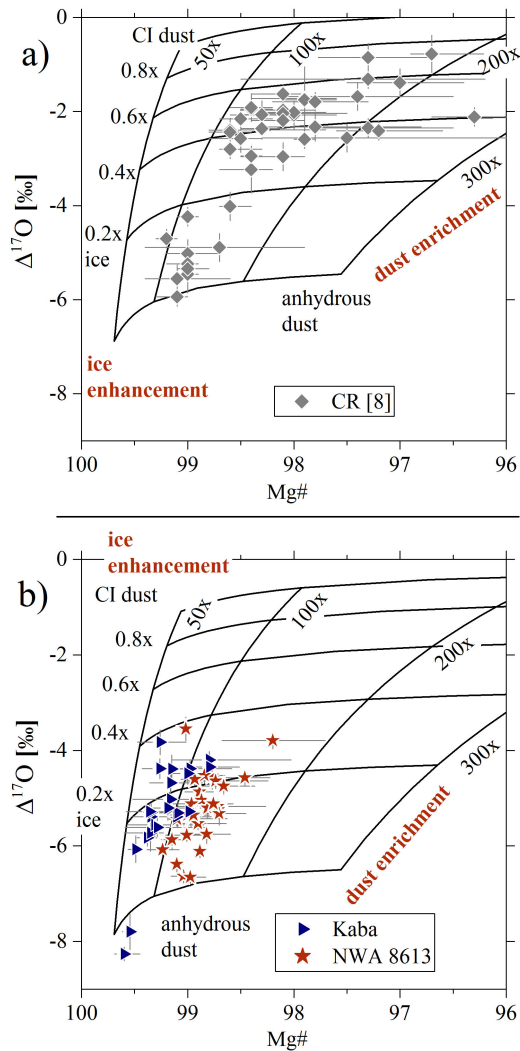


Fig. 1. Mg# - $\Delta^{17}\text{O}$ relationship of type I chondrules with Mg# > 96 in (a) two CR chondrites [8] and (b) Kaba and NWA 8613. Curves of constant dust enrichment and ice enhancement calculated by the model of [8]. Applied model parameters are those in [8], except for the $\Delta^{17}\text{O}$ value of anhydrous silicate dust in (b) (adjusted to -7‰). For NWA 8613, only Mg#'s of pyroxenes were used to calculate the mean.

By combining information on Mg#'s and $\Delta^{17}\text{O}$ values of chondrules, it is possible to examine the influence of the H_2O ice-to-dust ratio on the inferred dust enrichment factors. For instance, at anhydrous conditions, redox conditions needed to form chondrules with Mg#'s of ~ 99 , such as those in Kaba and NWA 8613, are reached at ~ 100 – $200\times$ dust enrichment. When adding water ice ($1\times$ the nominal water ice of CI dust), the required dust enrichment factor to form those chondrules decreases to $\sim 50\times$ (Fig. 1b). Thereby, the added water ice would raise the $\Delta^{17}\text{O}$ value of the chondrule significantly (from $\sim -7\text{‰}$ to $\sim -1\text{‰}$; $\Delta^{17}\text{O}$ water ice: $+5.1\text{‰}$,

silicate dust: -7‰), incompatible with determined $\Delta^{17}\text{O}$ values of chondrules in the two CV chondrites of this study. However, this assessment is sensitive to the assumed $\Delta^{17}\text{O}$ value of the silicate dust and, especially, to that of the water ice. A lower $\Delta^{17}\text{O}$ value of the water ice (e.g., 0‰) would lead to an underestimation of the ice enhancement. In any case, higher water-to-dust ratios would only lower the degree of dust enrichment required to form the bulk of chondrules in carbonaceous chondrites.

Variable water ice abundance during chondrule formation: [8] recognized that in the Mg#- $\Delta^{17}\text{O}$ diagram, type I chondrules from two CR chondrites plot along curves of constant dust enrichment. This leads the authors to suggest that variable amounts of water ice are responsible for this trend. Although less prominent, chondrules in Kaba and NWA 8613 also tend to show decreasing Mg#'s with increasing $\Delta^{17}\text{O}$ values (Fig. 1b). Within the scope of the model of [8], similar trends can be produced by applying different $\Delta^{17}\text{O}$ values of the silicate precursor dust and/or that of the water ice or by changing the water ice enhancement. It is important to highlight that chondrules from a single chondrite can show these systematic trends, suggesting that the controlling parameters, such as the ice enhancements, had to be variable on the level of individual chondrules. If variable ice enhancement factors are responsible for the systematic trends, then it is conceivable that those enhancements reflect the different ratios of the precursor silicate grains to the icy mantles that surround them. Relative anhydrous conditions recorded by type I chondrules in Kaba and NWA 8613 might have prevailed close the inner edge of the snow line.

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